ON THE ORIGIN OF TERRESTRIAL HEAT FLOW

by

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SUMMARY

It is proposed that at least part of the heat being transferred in terrestrial heat flow is due to a plastic release of the elastic stresses caused by the expansion of the Earth. This mechanism at the same time makes understandable the fact that terrestrial heat flow is independent of crustal structure.

The Earth as a thermodynamical system may be described by the relation between the heat loss, the amount of mechanical work and the change in internal energy as follows:

$$dQ = dW + dU$$

The value of dQ may be obtained if the value of heat flow rate is known. The latter is about $1{,}0-1{,}2\ \mu$ cal/cm^2 sec on the average. Calculating the flow for the entire surface of the Earth and for the period of one year we obtain $6 - 8 \cdot 10^{27}$ erg for the heat loss.

On the hand of the assumption of a contracting Earth, the value of dW was looked upon as positive, and attempts were made to derive at least part of dQ from contraction.

However, investigations on the Earth's interior have shown that instead of contracting, the Earth undergoes expansion [1, 2, 3]. The rate of expansion is such that the radius of the Earth increases by half a millimetre per year. The essentials of the Earth model from which the hypothesis of Earth expansion was derived are as follows:

The inner and outer core and the mantle of the Earth represent three different states of one and the same silicatic ground material. Of these three states, the two internal ones are unstable, so that the state of the inner core is continuously decaying into that of the outer core and the latter into that of the mantle. This process results in a decrease of the average density and consequently in an increase of the volume of the Earth.

This Earth model offers a possibility for estimating the amount of mechanical energy evolved. In the outlined process the internal energy works against the gravity field by lifting the mantle by at least half a millimetre per year. The work done is

$$dW = 4\,\pi\,R^2 \cdot dR \cdot g \cdot \Delta \cdot \sum \sigma$$

R being the Earth radius, $dR = 5 \cdot 10^{-2}$ cm the annual rate of increase of the same, Δ the thickness of the layer of density σ, and g the acceleration of gravity in the mantle. On computing this value we obtain $3{,}5 \cdot 10^{29}$ erg per year.

The presence of mechanical energy postulates a source wherefrom it can be derived. Consequently, the heat loss being about only 2 per cent of the energy computed above, the internal energy change has to be of the order of magnitude of $3{,}5 \cdot 10^{29}$ erg per year.

The source of the mechanical energy is assumed to be the state transition from the unstable state into the stable ones.

Let us compute the amount of energy attributed to one molecule. A radius increase by $\mathrm{d}R$ is equivalent to a volume change of

$$\mathrm{d}V = 4\pi R^2 \,\mathrm{d}R = 2{,}55 \cdot 10^{17} \text{ cm}^3$$

Let us denote the volume of the molecules undergoing the mentioned state change by V_0 before and by $V_0 + \mathrm{d}V$ after the same. The density of the mantle along the core boundary being 5,66 cgs, and that of the core being 9,71, it follows that

$$9{,}71\, V_0 = 5{,}66\,(V_0 + \mathrm{d}V)$$

or

$$V_0 = 1{,}4\, \mathrm{d}V = 3{,}56 \cdot 10^{17} \text{ cm}^3.$$

The mass of the transformed material is, consequently,

$$\mathrm{d}M = 9{,}71\, V_0 = 3{,}46 \cdot 10^{18} \text{ g}.$$

If the mantle is assumed with Birch [4] to consist of a mixture of Mg_2SiO_4 and Fe_2SiO_4, i. e. if the average molecular weight is 170, this same mass will be equivalent to

$$2{,}04 \cdot 10^{16} \text{ moles}.$$

Multiplying this by Avogadro's Number, $L = 6{,}02 \cdot 10^{23}$ mole^{-1}, the number of the molecules involved amounts to

$$n = 1{,}23 \cdot 10^{40}.$$

The energy in electronvolts necessary to lift the crust by the requisite amount is

$$\mathrm{d}W = 3{,}5 \cdot 10^{29} \text{ erg} = 1{,}19 \cdot 10^{41} \text{ eV}.$$

On this basis, the energy attributed to one molecule has to be

$$\frac{\mathrm{d}W}{n} = 17{,}8 \text{ eV}.$$

Considering that

$$\mathrm{d}W = 4\pi R^2 \cdot \mathrm{d}R \cdot g \cdot \Delta \cdot \sum \sigma = p \cdot \mathrm{d}V$$

p being the pressure on the core boundary, the above relation may be rewritten to read

$$\mathrm{d}U = p\mathrm{d}V^* = 17{,}8 \text{ eV}$$

equalling the energy liberated by the transition of one molecule from the metallic into the nonmetallic state.

The conduction band of a molecule, which gives rise to the metallic phase, exists also in the normal solid as an excited state. Its height above the ground level may be measured directly by the absorption of ultra-violet light. Taking into account the available data, the measurements on quartz are of more immediate interest. G l e a s o n has shown that the conduction band in quartz lies about 10,9 eV above the ground state. Comparing this value with the 17,8 eV obtained above, the agreement can be called more than good. The energy developed by such a state transition is, consequently, sufficient to bring about the volume increase postulated.

As regards now the heat loss of the Earth, this was formerly thought to go on at the expense of the internal heat reserve of our planet. Later on, after the discovery of radioactivity, it was attempted to deduce the heat radiation from radioactive decay, on the assumption that most of the crust consists of granite.

The heat generated by radioactivity in a granitic crust was quite sufficient to replace the heat lost and because of the absence of a granitic crust from beneath the oceans the heat flow was expected to be much less above the latter than above the continents. However, the latest investigations in the Pacific [5] had the remarkable result that with the exception of 3 anomalous places — where the heat flow rate was even greater than elsewhere — the average heat flow was 1,2 μ cal/cm^2 sec, while the average for the Atlantic was found to be 1,1 units. Consequently, the distribution of heat flow rate is independent of crustal structure.

The fact that the average heat flow in continental and oceanic areas is about equal can by no means be fortuitous ; on the contrary, it calls for an explanation of some kind. Moreover, it indicates the source of terrestrial heat flow to be situated at a great depth. Therefore, the idea to identify the material of the crust with that of granite intrusions has become illusory.

It can be shown, however, that the essential part of the thermal energy involved in heat flow may be derived from the energy liberated by the volume increase of the Earth. For, in consequence of the volume increase due to state transition, the particles of the mantle — being according to all observations, a solid — will undergo elastic deformation. The elastic energy stored up in a volume unit is approximately

$$w = k\,\theta^2$$

k being the incompressibility, and θ the relative volume change. Consequently, the energy of deformation in a part of the crust of volume V becomes

$$W = k\,\theta^2\,V$$

Clearly, the annual change in deformation energy will be

$$\frac{\mathrm{d}W}{\mathrm{d}t} = 2k\,\theta\,V\,\frac{\mathrm{d}\theta}{\mathrm{d}t}$$

Its value may be written, when assuming an annual radius increase of dR, as

$$\frac{\mathrm{d}W}{\mathrm{d}t} = \left[\frac{32\,\pi}{3} R^2 \cdot \mathrm{d}R \cdot \Delta \cdot \sum \frac{1-\sigma}{\varrho}\right] \cdot p = C \cdot p$$

σ being the Poisson-constant, Δ the thickness of the layer involved, ϱ the distance of the layer from the Earth's center and p the strength of material.

According to experiments, the value of p for rocks corresponding to the upper parts of the mantle is about $1-2 \cdot 10^{10}$ dyne per sq.cm [6]. On the other hand, the experiments of Goranson [7] have proved that the strength is almost independent of pressure. As by the above formula C equals $2{,}95 \cdot 10^{17}$ cgs and

$$10^{10} \leq p \leq 2 \cdot 10^{10} \text{ dyne cm}^{-2}$$

it follows that the relation

$$3 \cdot 10^{27} \text{ erg/year} \leq \Phi_0 \leq 6 \cdot 10^{27} \text{ erg/year}$$

will hold where Φ_0 is the annual heat flow. The heat flow thus estimated is seen to be of the same order of magnitude as the observed one.

Summing up we may state that part of the heat energy may be simply derived from the plastic release of elastic stresses accumulated in greater depths, whereby the energy of deformation is changed into heat energy. This process yields an essential part of the heat transported by heat flow and because of this the rate of the latter is independent of crustal structure.

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